Analytical strategies to measure gadolinium as a wastewater marker in surface and groundwater systems

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ABSTRACT

The increasing use of gadolinium (Gd)-based contrast agents in magnetic resonance imaging and the recalcitrant behavior of Gd during municipal wastewater treatment have led to increased concentrations of the tracer in aquatic environments. These anthropogenic Gd emissions to wastewater and, subsequently, to surface and groundwater systems can be exploited to calculate groundwater travel times and mixing ratios, identify wastewater inputs, and calibrate groundwater models. However, analytical complexity, costs, and the time needed to directly measure anthropogenic inputs hinder the practical use of Gd. While direct measurements with inductively coupled plasma-mass spectrometry (ICP-MS) are highly efficient and feasible, only total Gd can be detected with this approach. In unknown hydrogeological systems, the differentiation between total, anthropogenic, and geogenic Gd by interpolating rare earth element patterns requires complex sample pre-treatment and pre-concentration. Direct measurements of Gd can be obtained using anion-exchange chromatography coupled to ICP-MS but the limit of quantification will be higher. Here we provide guidelines for selecting the optimal method for the analysis of Gd as a wastewater tracer in surface-groundwater systems.

• The cost-effectiveness of existing analytical strategies to measure Gd when used as a wastewater tracer in surface-groundwater systems is addressed
• A novel analytical strategy for direct determination of total Gd is presented

Specification table

Subject area	Environmental Science
More specific subject area	*Hydrogeology*
Name of your method	*Strategies for gadolinium analytics in surface and groundwater systems*
Name and reference of original method	*Brünjes, R., Bichler, A., Hoehn, P., Lange, F.T., Brauch, H.J., Hofmann, T. Anthropogenic gadolinium as a transient tracer for investigating river bank filtration. Science of the Total Environment 571, 143, 1432–1440 (2016).*
	Macke, M., Derrick Quarles, C., Sperling, M., Karst, U. Fast and automated monitoring of gadolinium-based contrast agents in surface waters. Water Research 207, 117,836 (2021)
Resource availability	*concentrated HNO3 (3-fold subboiled, provided in analytically pure quality, Merck, Germany), analytical standards, H_2O_2 (31%, ROTIPURAN Ultra; Carl Roth, Germany), 15 mL centrifuge tubes (metal free), 50 mL centrifuge tubes (metal free)*

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Introduction

Gadolinium (Gd)-based contrast agents have been used in magnetic resonance imaging (MRI) since 1988 [1–4]. Since Gd complexes are very stable, they pass unmetabolized through the human body and are excreted via the urine. Only a small part of the injected Gd can accumulate in animal tissues [5,6]. However, Gd complexes are also recalcitrant in municipal wastewater treatment and are thus emitted into rivers, which has resulted in the accumulation of the tracer in aquatic environments. This anthropogenic Gd (Gd_{anth}) together with the natural geogenic Gd (Gd_{geo}) background comprises the total Gd (Gd_{total}) [7,8].

As the use of Gd is largely restricted to medical imaging, average Gd concentrations in WWTP effluents are typically in the order of 100 ng L^{-1} and thus an order of magnitude lower than the concentrations of other pollutants [9]. Since most MRI is performed on weekdays, Gd concentrations in wastewater tend to follow a weekly pattern, especially in small catchments [7,10]. The transient signal is detectable in surface waters affected by wastewater and is eventually propagated into groundwater, mostly via riverbank filtration [11–13]. Moreover, even in rural areas without MRI facilities, Gd_{anth} anomalies can be detected in groundwater affected by wastewater-impacted riverbank filtration, via the urinary excretion of Gd by outpatient treatment who have undergone MRI in larger towns and cities [7,11]. The transient Gd_{anth} concentrations measured in river water and the adjacent groundwater can be used to calculate groundwater travel times and riverbank filtrate mixing ratios [14]. Knowledge of both is crucial in managing and protecting drinking water supply systems close to rivers.

A prerequisite for the determination of Gd_{anth} in river water is a determination of Gd_{geo}, i.e., the natural background concentration of Gd, which in turn requires the measurement of other rare earth elements (REE) [2,3,15–19]. The determination of Gd_{anth} is therefore more tedious than the direct measurement of Gd_{total}. Furthermore, pre-concentration and thus advanced techniques are needed to reduce the limit of quantification (LOQ) to < 1 ng L^{-1}, especially in areas where both wastewater loads and the Gd_{geo} background are low [11]. However, whether Gd_{total} instead of Gd_{anth} can be used as a tracer in assessments of riverbank filtration systems is unclear.

In the following we discuss two existing methods to determine Gd complexes [20] and Gd_{anth} [11], propose a novel method for the rapid determination of Gd_{total}, and suggest guidelines for selecting the appropriate analytics in the use of Gd as a wastewater tracer in hydrogeology. These findings will be key to facilitate the use of Gd for investigating riverbank filtration systems and identifying wastewater inputs in surface-groundwater systems.

Method details

Anthropogenic gadolinium determination

In our determination of Gd, we used a column-based pre-concentration step that required degradation of the Gd_{anth} complexes [3]. After treatment with 5% (v/v) H_2O_2 (31%, ROTIPURAN Ultra; Carl Roth, Germany), the samples were exposed to UV-C light (254 nm, 4×15 W m^{-2}; Narva, Germany) for 24 h to degrade the Gd_{anth} complexes [8]. The samples were then placed in acid-prewashed UV-C light-transmissive polymethylpentene centrifuge tubes and sealed with acid-prewashed high-density polyethylene stoppers. Samples with Gd concentrations > 100 ng·L^{-1} were diluted by a factor of 50 prior to pre-treatment.

REE analysis for the calculation of Gd_{anth} was performed using an on-line SeaFAST 2 pre-concentration system (Elemental Scientific Inc., USA; [21]) coupled to an Agilent 8800 Triple Quad inductively coupled plasma-mass spectrometry (ICP-MS) instrument (Agilent Technologies, Japan), which achieved the LOQ values needed to accurately distinguish Gd_{anth} from Gd_{geo}. The LOQ of Gd was ≤ 0.1 ng L^{-1} (SD ≤ 0.04 ng L^{-1}); the values for samarium (Sm) and terbium (Tb) were ≤ 0.01 ng L^{-1} (SD ≤ 0.001 ng L^{-1}).

The Gd_{geo} concentration, required for the calculation of Gd_{anth} in Gd_{total} using Eq. (1), was interpolated from the concentrations of Gd and its neighboring REE elements Sm and Tb. The latter were normalized to the upper continental crust (UCC) [22], as shown in Eq. (2) (after [2]) with an SD ≤ 0.1 ng L^{-1}.

$$Gd_{anth} = Gd_{total} - Gd_{geo} \tag{1}$$

$$Gd_{geo} = \left(0.33 \frac{Sm_{measured}}{Sm_{UCC}} + 0.67 \frac{Tb_{measured}}{Tb_{UCC}} \right) Gd_{UCC} \tag{2}$$

Other methodologies used to calculate Gd_{geo}, including their applicability, advantages, and disadvantages, are discussed in detail in Brünjes and Hofmann [3]. However, they may require the measurement of all REE and should thus be selected carefully. For example, for the third-order polynomial fit proposed by Möller et al. [11], all lanthanides need to be measured precisely.

Anion-exchange chromatography to separate and detect Gd complexes

A fast (< 2 min chromatographic run time) hyphenated method to separate and detect Gd complexes was described by Macke et al. [18]. It is based on syringe-driven anion-exchange chromatography used in combination with ICP-MS, to separate and measure the five Gd complexes commonly administered to patients in the European Union (Gd-HP-DO3A, Gd-BT-DO3A, Gd-DOTA, Gd-DTPA, and Gd-BOPTA). External calibration was performed using an automated in-line dilution function, which allowed precise calibration from single stock standards. This method, when coupled with quadrupole ICP-MS, resulted in a low LOQ (Table 1). The species-specific LOQ values were between 21.2 and 68.8 ng L^{-1} at a chromatographic run time of < 2 min. These values refer to the respective concentrations of the Gd complexes. The LOQ of the Gd element concentration was between 5.98 and 10.2 ng L^{-1}.

Table 1

Limit of detection (LOD) and limit of quantification (LOQ) values of the Gd-complexes in their entirety and of the Gd concentration alone, as reported by Macke et al. [18].

Component	LOD (complex) [ng L^1]	LOQ (complex) [ng L^1]	LOD (Gd) [ng L^1]	LOQ (Gd) [ng L^1]
Gd-HP-DO3A	7.82	25.1	2.20	7.08
Gd-BT-DO3A	6.65	23.0	1.73	5.98
Gd-DOTA	6.14	21.2	1.73	5.98
Gd-DTPA	7.67	25.7	2.20	7.39
Gd-BOPTA	20.1	68.8	2.99	10.2

Table 2

The ICP-MS operation parameters needed to obtain optimal measurement results using the direct Gd_{total} method.

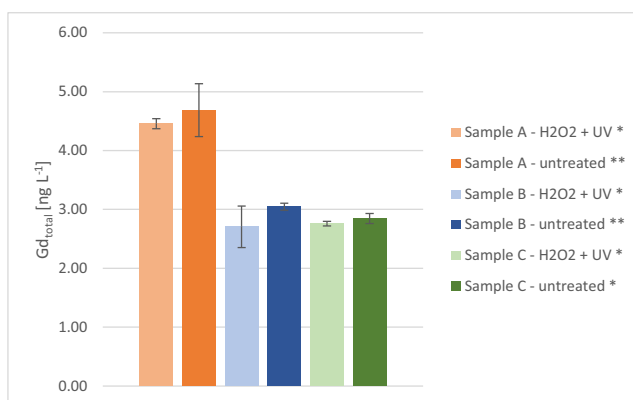| Operation parameter	Setting
RF power (W)	1550
RF matching (V)	1.8
Sample depth (mm)	6
Nebulizer gas flow (l/min)	1
Data acquisition	
Acquisition mode	Peak hopping
Dwell time (ms)	80
Integration time (s)	0.1/point
Repetition	5 (FullQ)

Fig. 1. Samples pre-treated or not with H_2O_2 and UV exposure and then measured using the direct Gd_{total} method. * measured as duplicates; ** measured as triplicates.

Direct total gadolinium determination

We propose that if the Gd_{anth} concentration surpasses the natural Gd_{geo} background by at least one order of magnitude, a separation of natural and anthropogenic Gd sources is no longer required in order to use Gd as a simple marker in hydrogeology. This eliminates the need to measure other or all REE [11,20]. Moreover, since ICP results in the complete ionization of pharmaceutical Gd complexes, the time-consuming sample preparation (H_2O_2, exposure to UV-C light) needed for chromatographic pre-concentration is eliminated as well (Fig. 1).

Direct measurements of Gd_{total} were performed using an Agilent 7900 Single Quad ICP-MS instrument (Agilent Technologies, Japan) in no-gas mode. To increase the sensitivity for Gd_{total} the plasma distance was decreased to 6 mm, although this results in greater wear of the sample cone. The instrument conditions providing optimal measurement results are reported in Table 2. In this configuration, the LOQ of Gd_{total} was ≤ 3.0 ng L^{-1} and the SD ≤ 0.2. However, the LOQ values for Sm and Tb were ≤ 0.84 ng L^{-1} and ≤ 0.06 ng L^{-1}, which were not precise enough to cover the natural range of the respective elements. The interpolation of Gd_{geo} using the rapid method was therefore not possible.

Cost-efficient strategies for the analysis of Gd in hydrogeology: conclusion and outlook

In this paper, three different ICP-MS based analytical methods for the determination of total, anthropogenic, and the pharmaceutical Gd complexes in surface and groundwater were presented: (1) Direct measurement of Gd with ICP-MS allows the fast and cost-efficient measurement of Gd_{total}. (2) The determination anthropogenic gadolinium by measuring a large suite of REE enables the separation of Gd_{anth} and Gd_{geo}. (3) Using a hyphenated anion-exchange chromatography, the pharmaceutical species itself can be detected. However, the three presented methods vary considerably in terms of their time, costs, and detection limit.

For an unknown hydrogeological system, Gd_{total}, Gd_{anth}, Gd_{geo} can be determined by analyzing the extended REE pattern (Sect. 2.1). The most suitable calculation method should be chosen as described in Hofmann & Brünjes [3]. If this pre-testing shows that Gd_{anth} is > 10-fold higher than Gd_{geo}, indicating significantly high wastewater inputs, direct measurement of Gd by ICP-MS is recommended. This method is both faster and cheaper than either on-line SeaFAST pre-concentration (Sect. 2.1) or hyphenated anion-exchange chromatography (Sect. 2.2). The rapid and cost-efficient direct detection facilitates the use of large sample sets of Gd_{total} to calibrate groundwater models and to estimate groundwater residence times, groundwater mixing ratios, and the fraction of wastewater inputs to drinking water supply systems.

For unknown groundwater systems with expected inputs from electronic or other industries, the determination of Gd_{anth}, Gd_{geo}, and Gd_{total} is strongly recommended. Online SeaFAST and off-line preconcentration result in very low LOQ values and allow the measurement of REE, needed to interpolate the Gd_{geo} fraction. In this case, we recommend using the calculation based on all lanthanides developed by Möller et al. [11].

Anion-exchange chromatography coupled to ICP-MS is appropriate when different sources of Gd must be separated and direct proof of medical anthropogenic Gd inputs is required. The good LOQ of this approach enables its application when wastewater inputs are relatively low.

Gd is not used as a regular tracer to determine wastewater inputs regularly. We suggest a larger round-robin test, and standardized ISO protocols for the measurement of gadolinium in drinking water, including other REE to correct for anthropogenic and geogenic gadolinium.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

References

[1] W. Gibby, W. Parish, R.M. Merrill, D. Fernandez, C.R. Anderson, E. Merchel, R. Parr, The use of a binary chelate formulation: could gadolinium based linear contrast agents be rescued by the addition of zinc selective chelates? Magn. Reson. Imaging. 58 (2019) 76–81, doi:10.1016/j.mri.2019.01.001.

[2] M. Bau, P. Dulski, Anthropogenic origin of positive gadolinium anomalies in river waters, Earth Planet. Sci. Lett. 143 (1996) 245–255, doi:10.1016/0012-821x(96)00127-6.

[3] R. Brünjes, T. Hofmann, Anthropogenic gadolinium in freshwater and drinking water systems, Water Res. 182 (2020) 115966, doi:10.1016/j.watres.2020.115966.

[4] K. Schmidt, M. Bau, G. Merschel, N. Tepe, Anthropogenic gadolinium in tap water and in tap water-based beverages from fast-food franchises in six major cities in Germany, Sci. Total Environ. 687 (2019) 1401–1408, doi:10.1016/j.scitotenv.2019.07.075.

[5] H. Richter, P. Bücker, L.F. Martin, C. Dunker, S. Fingerhut, A. Xia, A. Karol, M. Sperling, U. Karst, A. Radbruch, A. Jeibmann, Gadolinium tissue distribution in a large-animal model after a single dose of gadolinium-based contrast agents, Radiology 301 (2021) 637–642, doi:10.1148/radiol.2021210553.

[6] M. Kobayashi, S.R. Levendovszky, D.S. Hippe, M. Hasegawa, N. Murata, K. Murata, D.A. Marshall, L.F. Gonzalez-Cuyar, K.R. Maravilla, Comparison of human tissue gadolinium retention and elimination between gadoteridol and gadobenate, Radiology 300 (2021) 559–569, doi:10.1148/radiol.2021204320.

[7] K. Kümmerer, E. Helmers, Hospital effluents as a source of gadolinium in the aquatic environment, Environ. Sci. Technol. 34 (2000) 573–577, doi:10.1021/es990633h.

[8] P.L. Verplanck, E.T. Furlong, J.L. Gray, P.J. Phillips, R.E. Wolf, K. Esposito, Evaluating the behavior of gadolinium and other rare earth elements through large metropolitan sewage treatment plants, Environ. Sci. Technol. 44 (2010) 3876–3882, doi:10.1021/es903888t.

[9] R. Loos, R. Carvalho, D.C. António, S. Comero, G. Locoro, S. Tavazzi, B. Paracchini, M. Ghiani, T. Lettieri, L. Blaha, B. Jarosova, S. Voorspoels, K. Servaes, P. Haglund, J. Fick, R.H. Lindberg, D. Schwesig, B.M. Gawlik, EU-wide monitoring survey on emerging polar organic contaminants in wastewater treatment plant effluents, Water Res. 47 (2013) 6475–6487, doi:10.1016/j.watres.2013.08.024.

[10] L. Telgmann, C.A. Wehe, M. Birka, J. Künnemeyer, S. Nowak, M. Sperling, U. Karst, Speciation and isotope dilution analysis of gadolinium-based contrast agents in wastewater, Environ. Sci. Technol. 46 (2012) 11929–11936, doi:10.1021/es301981z.

[11] R. Brünjes, A. Bichler, P. Hoehn, F.T. Lange, H.-J. Brauch, T. Hofmann, Anthropogenic gadolinium as a transient tracer for investigating river bank filtration, Sci. Total Environ. 571 (2016) 1432–1440, doi:10.1016/j.scitotenv.2016.06.105.

[12] M. Rabiet, F. Brissaud, J.L. Seidel, S. Pistre, F. Elbaz-Poulichet, Positive gadolinium anomalies in wastewater treatment plant effluents and aquatic environment in the Hérault watershed (South France), Chemosphere 75 (2009) 1057–1064, doi:10.1016/j.chemosphere.2009.01.036.

[13] A. Bichler, C. Muellegger, R. Brünjes, T. Hofmann, Quantification of river water infiltration in shallow aquifers using acesulfame and anthropogenic gadolinium, Hydrol. Process. 30 (2016) 1742–1756, doi:10.1002/hyp.10735.

[14] A. Knappe, P. Möller, P. Dekdeger, Positive gadolinium anomaly in surface water and ground water of the urban area Berlin, Germany, Chemie Der Erde 65 (2005) 167–189, doi:10.1016/j.chemer.2004.08.004.

[15] P. Möller, T. Paces, P. Dulski, G. Morteani, Anthropogenic Gd in surface water, drainage system, and the water supply of the City of Prague, Czech Republic, Environ. Sci. Technol. 36 (2002) 2387–2394, doi:10.1021/es010235q.

[16] C. Hissler, P. Stille, C. Guignard, J.F. Iffly, L. Pfister, Rare earth elements as hydrological tracers of anthropogenic and critical zone contributions: a case study at the Alzette River Basin Scale, Procedia Earth Planet. Sci. 10 (2014) 349–352, doi:10.1016/j.proeps.2014.08.036.

[17] T. Ogata, Y. Terakado, Rare earth element abundances in some seawaters and related river waters from the Osaka Bay area, Japan: significance of anthropogenic Gd, Geochem. J. 40 (2006) 463–474, doi:10.2343/geochemj.40.463.

[18] S. Kulaksız, M. Bau, Anthropogenic dissolved and colloid/nanoparticle-bound samarium, lanthanum and gadolinium in the Rhine River and the impending destruction of the natural rare earth element distribution in rivers, Earth Planet. Sci. Lett. 362 (2013) 43–50, doi:10.1016/j.epsl.2012.11.033.

[19] S. Kulaksiz, M. Bau, Anthropogenic gadolinium as a microcontaminant in tap water used as drinking water in urban areas and megacities, Appl. Geochemistry. 26 (2011) 1877–1885, doi:10.1016/j.apgeochem.2011.06.011.

[20] M. Macke, C.D. Quarles, M. Sperling, U. Karst, Fast and automated monitoring of gadolinium-based contrast agents in surface waters, Water Res. 207 (2021) 117836, doi:10.1016/j.watres.2021.117836.

[21] E.C. Hathorne, B. Haley, T. Stichel, P. Grasse, M. Zieringer, M. Frank, Online preconcentration ICP-MS analysis of rare earth elements in seawater, Geochem., Geophys. Geosyst. 13 (2012) 1–12, doi:10.1029/2011GC003907.

[22] S.R. Taylor, S.M. McLennan, The Continental Crust: its Composition and Evolution, Blackwell Scientific Pub., Palo Alto, CA, United States, 1985 https://www.osti.gov/biblio/6582885.